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Solar Thermal Power: Appraisal of Solar Power Towers

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Abstract. This study delves into several engineering procedures related to solar power tower plants. These installations come with central receiver system technologies and high-temperature power cycles. Besides a summary emphasizing on the fundamental components of a solar power tower, this paper also forwards a description of three receiver designs. Namely, these are the tubular receiver, the volumetric receiver and the direct absorber receiver. A variety of heat transfer mediums were assessed, while a comprehensive explanation was provided on the elements of external solar cylindrical receivers. This explanation covers tube material, molten salt, tube diameter and heat flux.

1 Introduction

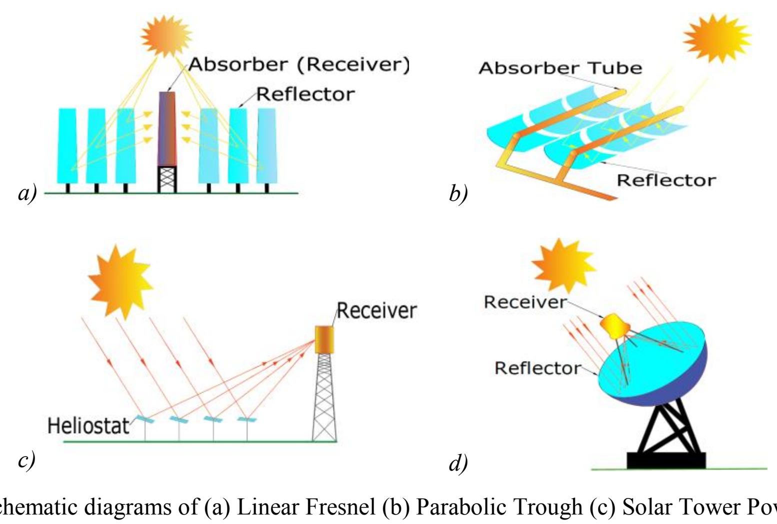

Fig. 1. Schematic diagrams of (a) Linear Fresnel (b) Parabolic Trough (c) Solar Tower Power (d) Parabolic Dish.

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Solar thermal power systems belong to an area of technology that focuses on the exploitation of heat energy from the sun. The reflection of concentrated solar radiation onto a fluid medium serves to produce heat which is harnessed for electricity generation. In accordance to their configuration, there are generally four types of solar thermal power systems as shown in Fig. 1. These are the solar tower power system, the parabolic dish system, the parabolic trough system, and the linear Fresnel system. The solar receiver in the solar power tower system is sited at the tower's focal point. It receives the concentrated sunlight for heating up the heat transfer fluid (HTF) by way of heliostats. These concentration techniques are deemed adept for the generation of elevated temperatures as well as exceptional thermodynamics.

2 Solar power towers (SPTs)

Solar power towers are also referred to as central receiver systems [1]. These systems are equipped with tracking mirrors called heliostats which are located around a main external receiver. This receiver is mounted on the top of the tower at the focal point of the heliostats. The central solar tower is acknowledged as the most effective system for the generation of raised temperatures [2]. This system boasts the capacity to realize a solar flux degree which is consistently above 600 sun (1 sun=1000W/m^2). Among all the currently available solar thermal power systems, the central solar tower system is deemed the most competent.

2.1 Standard central receivers

The most frequently employed central receivers are the tubular, volumetric, and direct absorption receivers.

2.1.1 Tubular receivers

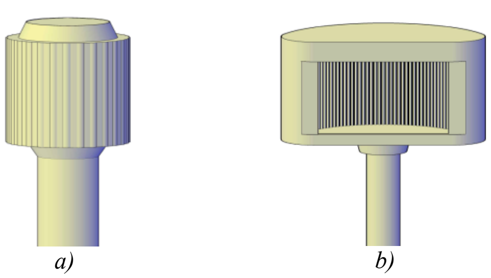

Fig. 2. a) External Cylindrical receiver. b) Internal Cavity receiver.

Depending on the kind of receiver employed, compilations of parallel tubes are assembled to fashion a cylinder, or semi-cylinder. The temperature of the tubes are lowered on the inside by the HTF, and raised on the outside through concentrated sunlight. While half the tubes' circumference is subjected to solar irradiance, the other half can be deemed adiabatic. Tubular receivers are employed for the transference of liquid heat through fluids that include molten salt, water, thermic oil, liquid metals and Hitec salt [3-4]. Tubular receivers can be separated into two categories: external and internal. External cylindrical receivers come with spherical, slender-walled metal tubes. These tubes are assembled alongside each other in a cylindrical formation. This can be observed in Figure 2-a. The solar flux forwarded from the heliostats swing from every direction. As shown in Figure 2-b, the internal cavity receiver comes with a minute aperture [5] . This receiver decreases losses attributed to convection by positioning its welded tubes within a cavity. The two kinds of cavity receivers are the single and dual cavity receivers.

2.1.2 Volumetric receivers

With these receivers, the HTF comes in the form of air or supercritical CO_2. There are two fundamental kinds of volumetric receivers. In the open volumetric air receiver, atmospheric air represents the heat transfer medium. These receivers comprise permeable absorbers made up of high temperature resilient substances. These substances include wire-mesh, ceramic monoliths, foams, knit-wire packs and foil arrangements [6-7]. Ambient air flowing through the porous configuration soaks up a substantial measure of heat. This heat is subsequently harnessed for the generation of steam [8]. The other kind of volumetric receiver is the closed volumetric receiver (also known as the pressurized air receiver). This receiver comes in the form of an internally insulated pressure container covered by a quartz glass window in the profile of a dome. Concentrated solar radiation flows through the quartz glass window, and eventually arrives at the absorbing structure located at the rear of the window in the container. The radiation raises the temperature of the absorbing structure, and this heat is imparted to the air travelling through the structure.

2.1.3 Direct absorption receivers

In these receivers, the concentrated solar radiation is absorbed by the heat transfer medium in a straightforward manner. Direct absorption receivers come in two forms: solid particle receivers and centrifugal receivers. While the former involves the descending of ceramic particles directly into a cavity receiver [9], the latter involves an inclined rotating cylindrical cavity with descending particles directly heated by solar radiation [10].

2.2 Heat transfer mediums

The form of heat transfer medium employed in solar towers is determined by the type of receiver and power cycle involved. Heat transfer mediums include fluids and solid particles. Heat transfer fluids can be categorized into five groups: oil-based, water-based, liquid metals, molten salts and gases. Molten salt and water are suitable for solar towers, and both, as well as oil, is appropriate for the parabolic trough and linear Fresnel systems. Air, helium, CO_2 and nitrogen are examples of gases that can be utilized as heat transfer mediums. Solid particles used as heat transfer mediums come in the form of directly heated ceramic-based materials [11]. Supercritical fluids favoured as a transfer medium include supercritical water (due to the elevated critical pressure of water) [12], and carbon dioxide (which comes with a substantially lower critical pressure) [13].
The choice of an appropriate heat transfer medium is determined by several issues. These include its melting point, boiling point, thermal conductivity, viscosity, specific heat capacity, cost effectiveness, pollution effects, flammability, and compatibility in relation to other materials.

3 External cylindrical receiver designs

In 1981, the earliest large-scale electricity producing facility (Solar One) was fully constructed and ready for testing. It was set up with the objective of utilizing receiver steam for the generation of 10 MWe net [14]. Water/steam, the HTF employed, was superheated to 510°C at 10.3 MPa. The ultimate temperature in the turbine dropped to 280°C with a gross cycle efficiency equivalent to 28% [15]. Over the last ten years, researchers in this domain have worked to improve the design of receivers in order to decrease the loss of heat, and the occurrence of receiver malfunction. Specifications of Central tower projects around the world with Steam Rankine cycle listed in Table 1.

Table 1. Global Concentrating solar power (CSP) projects that use power tower systems [16-18]

Project Name	Receiver Type	Location	Tower Height (m)	Receiver Outlet Temp. (°C)	Turbine Capacity (Gross) MW	Heat Transfer Fluid	Start Year
ACME Solar Tower	Central	India	46	440	2.5	Water/ Steam	2011
Atacama-1	External receiver	Chile	243	550	110.0	Molten Salt	2018
Crescent Dunes Solar Energy Project	External - cylindrical	United States	195	565.5	110.0	Molten salt	2015
Dahan Power Plant	Cavity	China	118	400	1.0	Water/ Steam	2012
Gemasolar Thermosolar Plant	External tube receiver	Spain	140	565	19.9	Molten salts	2011
Jülich Solar Tower	Open volumetric	Germany	60	680	1.5	Air	2008
Planta Solar 10 (PS10)	Cavity	Spain	115	250-300	11.02	Water	2007
Sierra Sun Tower Sierra	Dual-cavity & tubular external	United States	55	440	5.0	water	2009

3.1 Receiver tube material

The materials used for receiver tubes are required to be highly durable and exceptionally resistant against rust as well as thermo-mechanical fatigue (TMF). Additionally, these materials need to come with a raised sun radiation absorption capacity and the ability to endure extreme pressures. The tube material used in Solar One was 316 L stainless steel with a controlled nitrogen content [19], 316 L stainless steel was also used in Solar Two [20], nickel alloy steel was used in Solar Tres [21], while a nickel-chromium alloy was opted for in Gemasolar [22].

3.2 Molten salt

Molten salts have the capacity to perform as a HTF at temperatures as high as 600°C. Besides being non-flammable and non-toxic, molten salts are also equipped with appropriate thermos-physical features for the transference of heat. These features include a low melting point (which serves to avert solidification), an elevated thermal conductivity level, a high heat capacity level, and a low viscosity level. The physical characteristics of the three major salts utilized as HTFs (molten salt, hitec and hitec XL) are displayed in Table 2.

Table 2: Physical properties of molten-salt heat-transfer fluids [5, 23-25]

Molten salt	Composition by Wt.	Melting Point (°C)	Upper Temperature limit (°C)	Heat Capacity (J/kg K)	Density (kg/m^3)	Conductivity (W/m K)
$NaNO_3$ KNO_3	0.60 0.40	220	600	1517	1817	0.49
$Ca(NO_3)_2$ $NaNO_3$ KNO_3	0.48 0.07 0.45	133	500	1447	1992	n/a
KNO_3 $NaNO_2$ $NaNO_3$	0.53 0.40 0.07	142	535	1560	1640	0.483

3.3 Receiver design

The external and internal diameters of a receiver's tube significantly influence the receiver's capacity for managing the various levels of high heat flux. This is noteworthy as high heat flux can result in extensive thermal stresses and strains. The diameter of receiver tubes ranges from 20mm to 45mm [26]. While an undersized tube diameter boosts the velocity to improve the receiver's performance, the downside is that this circumstance also leads to an increased dip in pressure.

3.4 Heat flux

The extent of heat flux influence is determined by the materials used for the crafting of the tube and the HTF employed. For the water or steam the Allowable heat flux value near 0.5 MW/m^2 , while it is around 1 MW/m^2 for the molten salt, and fluctuate near 1.5 MW/m^2 for liquid sodium [15].

Conclusion

The fashioning of a molten salt solar receiver is made difficult by several issues. While molten salt holds an edge over standard HTFs, the chemistry of salt is such that the establishment of a balance between economic and technical risks poses a significant challenge. A low melting point supported by a high heat capacity and density will serve to decrease the number of storage tanks needed. This in turn will lead to a more cost-effective operation. The need to perform under raised operating temperatures demands the use of costly materials for the crafting of the receiver's tube. The use of inferior materials is highly risky as this may lead to extensive losses and/or technical problems. The peak temperatures of the receiver are anticipated to come close to 800°C for a receiver outlet salt temperature of 720°C. The construction of receivers using materials capable of enduring extreme stress levels will enable receivers to operate under higher temperatures.

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